EPJ Web of Conferences **35**, 06002 (2012)
DOI: 10.1051/epjconf/20123506002
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Observation of new $h_{9/2}$ and $h_{11/2}$ bands in ^{187}Tl

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Abstract. The unfavoured signature of the rotation-aligned band associated with the prolate $h_{9/2}$ structure in ^{187}Tl has been identified. The deformation-aligned $11/2^{-}[505]$ band is also confirmed and extended. While the alignment properties of the $11/2^{-}[505]$ band seem to indicate that it has a similar magnitude of deformation as the prolate ^{186}Hg core, the signature splitting at low spin, taken together with new self-consistent calculations, suggest that it may actually be triaxial with $\gamma \approx -18^{0}$ near the bandhead.

1 Introduction and Experimental Information

Neutron-deficient nuclei near the Z=82 closed shell exhibit the phenomenon of shape coexistence, in which the nucleus can take on a variety of shapes; oblate, prolate, and even spherical, at low excitation energy [1]. Previous studies of ^{187}Tl deduced that coexisting prolate and oblate shapes were present on the basis of characteristic level structures [2,3]. These shapes were also assigned from direct quadrupole moment measurements [4]. Long-lived states with microsecond lifetimes were also observed in ^{187}Tl [5], but their shape and configuration was uncertain.

A new study of ^{187}Tl was undertaken at the Lawrence Berkeley National Laboratory, using a heavy-ion fusion-evaporation reaction involving a beam of 154 MeV ^{32}S ions incident on a 1.2 mg/cm^2 ^{159}Tb target, backed with 4.5 mg/cm^2 of ^{197}Au. The beam from the 88-inch cyclotron was pulsed at 60 ns intervals and the emitted gamma-rays were detected by the Gammasphere array. The structure of ^{187}Tl was studied using the techniques of gamma-ray spectroscopy, yielding a comprehensive level scheme.

This paper reports only on the observation of the unfavoured signature of the prolate $h_{9/2}$ band and the extensions of the (now confirmed) $h_{11/2}$ structure. Full results will be presented in a later publication [6].

2 Results

Figure 1 shows a partial level scheme for ^{187}Tl, in which a new band was observed to feed the known [3] "$h_{9/2}$" band in ^{187}Tl. The transitions in this band are evident in the γ-ray coincidence spectrum shown in Figure 2. The angular distribution of the strongest interband transition at 564.1 keV suggests a dipole character, while the in-band transitions appear to be quadrupoles. This is consistent with its interpretation as a $\Delta J = 2$ band with $M1$ transitions to the main "$h_{9/2}$" band. The assignment of this structure as the unfavoured signature of the "$h_{9/2}$" band will be discussed in section 3.1.

A regular rotational band feeding the oblate $9/2^{-}[505]$ rotational band was also identified (see Figure 3). Most of the transitions in this band are seen in the γ-ray coincidence spectrum in Figure 4.

The angular distributions of the 223.1 and 617.1 keV γ-rays deexciting the 952 keV state were measured, and a χ^2 minimisation was performed to compare with theoretical values. Figure 5 shows the reduced χ^2 values (χ^2/ν) as a

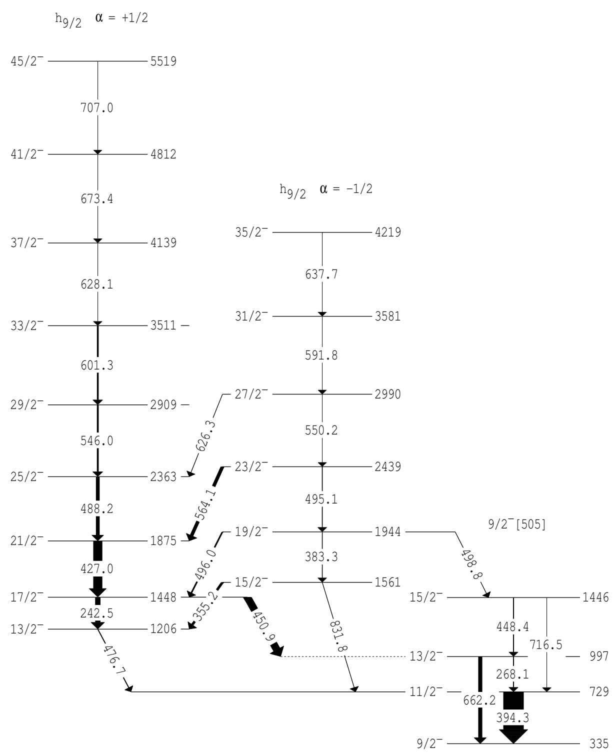

Fig. 1. Partial level scheme of ^{187}Tl showing both signatures of the prolate $h_{9/2}$ structure decaying into the oblate $9/2^{-}[505]$ rotational band. (The $9/2^{-}$ state is not the ground state, but β-decays to ^{187}Hg with a half-life of 15.6(1) s [7].)

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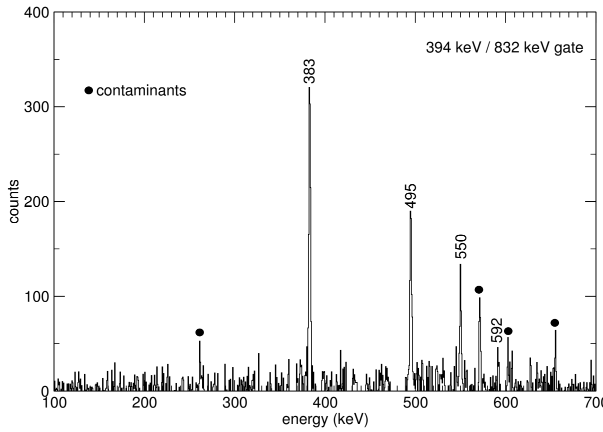

Fig. 2. Coincidence spectrum double-gated on the 394.3 and 831.8 keV γ-rays, showing transitions in the unfavoured signature of the prolate $h_{9/2}$ structure.

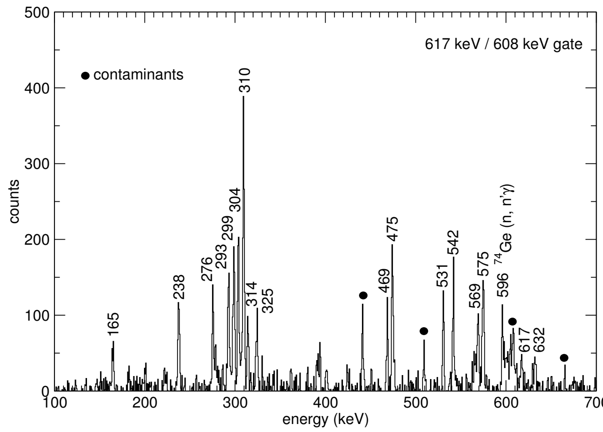

Fig. 4. Coincidence spectrum double-gated on the 617.1 and 607.7 keV γ-rays, showing transitions in the $11/2^{-}[505]$ band.

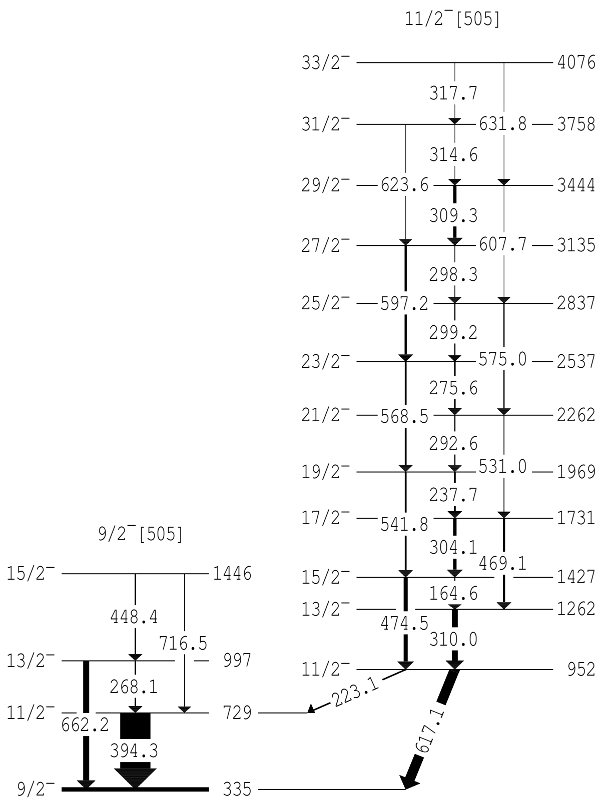

Fig. 3. Partial level scheme of ^{187}Tl showing the $11/2^{-}[505]$ band and its decay to the $9/2^{-}[505]$ band.

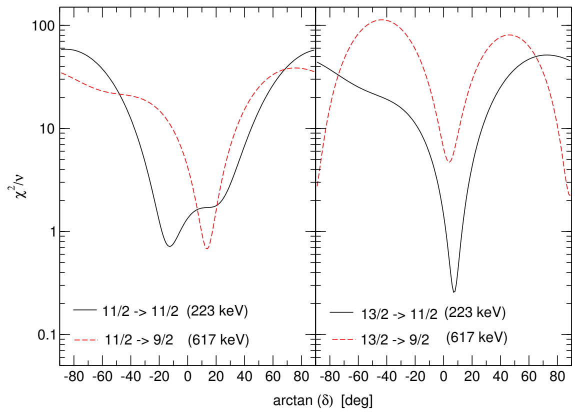

Fig. 5. Angular distribution χ^2 analysis for the 223.1 and 617.1 keV transitions.

function of the transition mixing ratio δ, assuming spins of 11/2 (left panel) and 13/2 (right panel) for the 952 keV state. The measured lifetime limit for the 952 keV state from $\gamma-\gamma$ time differences is $\tau < 3$ ns.

For a spin of 13/2, minima at $\delta \to \pm\infty$ are seen for the 617.1 keV transition. This would imply it was either a pure $M3$ or $E3$ transition, with unphysical transition strengths of $> 5.4(4) \times 10^5$ or $> 6.3(4) \times 10^3$ W. u. respectively. Looking at the other solutions for δ gives the limits on the transition strengths shown in Table 1. From the values for the $M2$ components, the 952 keV state cannot have $J^\pi = 11/2^+$ or $13/2^+$.

In order to decide between the $J^\pi = 11/2^-$ and $13/2^-$ possibilities, expected values of the intensity ratio between

Table 1. Transition strengths of the 223.1 and 617.1 keV γ-rays for various spins and parities of the 952 keV state.

J^π	E_γ (keV)	$X\lambda$	I_γ	α_T	Trans. Strength (W. u.)
$\frac{11}{2}^-$	223.1	$M1$	$24(7)^a$	0.887	$> 9(4) \times 10^{-5}$
	223.1	$E2$	$2.0(6)^a$	0.282	$> 6(2) \times 10^{-2}$
	617.1	$M1$	$184(57)^b$	0.0572	$> 3(1) \times 10^{-5}$
	617.1	$E2$	$3(1)^b$	0.0173	$> 6(3) \times 10^{-4}$
$\frac{11}{2}^+$	223.1	$E1$	$24(7)^a$	0.0581	$> 10(4) \times 10^{-7}$
	223.1	$M2$	$2.0(6)^a$	4.01	$> 7(3)$
	617.1	$E1$	$184(57)^b$	0.0060	$> 4(2) \times 10^{-7}$
	617.1	$M2$	$3(1)^b$	0.156	$> 7(3) \times 10^{-2}$
$\frac{13}{2}^-$	223.1	$M1$	$26(1)^c$	0.887	$> 1.0(1) \times 10^{-4}$
	617.1	$E2$	$187(9)^c$	0.0173	$> 3.7(2) \times 10^{-2}$
$\frac{13}{2}^+$	223.1	$E1$	$26(1)^c$	0.0581	$> 9.6(6) \times 10^{-7}$
	617.1	$M2$	$187(9)^c$	0.156	$> 3.9(3)$

[a] I_γ deduced using $\delta = -0.23(7)$ from the angular distribution.
[b] I_γ deduced using $\delta = 0.13(4)$ from the angular distribution.
[c] I_γ deduced using $\delta \approx 0$ from the angular distribution.

the 223.1 and 617.1 keV γ-rays have been calculated assuming that the transitions are pure $M1$ ($11/2^-$) or $M1$ and $E2$ ($13/2^-$) with all the strengths being 1 W.u. These values are compared to the measured branching ratio (see Table 2). The expected branching ratio for the $J^\pi = 11/2^-$ possibility agrees with the measured value, but for the $J^\pi = 13/2^-$ case, the expected ratio is more than ~ 350 times

Table 2. Ratio of observed γ-ray intensities for the 223.1 and 617.1 keV transitions compared with the expected values for alternative spin assumptions for the 952 keV state (see text for further details).

J^{π}	$I_{\gamma}(617.1)/I_{\gamma}(223.1)$ [measured]	$I_{\gamma}(617.1)/I_{\gamma}(223.1)$ [expected]
$11/2^-$	7.2(5)	20(13)
$13/2^-$	7.2(5)	0.020(2)

less than the measured value. Hence, the 952 keV level is assigned the spin of $11/2^-$, consistent with it being the $11/2^-[505]$ bandhead that is expected at low excitation energy.

3 Discussion

3.1 The unfavoured signature of the $h_{9/2}$ band

The alignment of the single-particle angular momentum to the rotation axis, i_x, can be obtained by subtracting the (parametrised) rotational angular momentum of the collective core. Figure 6 plots the alignments for the $h_{9/2}$ bands in ^{187}Tl, ^{183}Au and ^{185}Au as a function of the rotational frequency $\hbar\omega$. The reference parameters that are used, $\mathcal{I}_0 = 27\ MeV^{-1}\hbar^2$ and $\mathcal{I}_1 = 190\ MeV^{-3}\hbar^4$, are the same as those used in Ref. [12], where they were chosen to produce $i_x \approx 0$ for the prolate cores of even-even mercury nuclei around N=104 (see, for example, Fig. 2 in Ref [12] and Fig. 7 below).

In an odd-mass nucleus, a difference of $\sim 1\hbar$ is expected between the alignments of the favoured and unfavoured signatures of a rotational band when the Fermi level is close to the $\Omega = 1/2$ orbital of a high-j particle, so that the odd particle is fully aligned to the rotation axis [8]. Hence, the rotation-aligned $h_{9/2}$ proton in ^{187}Tl, which mainly occupies the $\pi 1/2^-[541]$ and $\pi 3/2^-[532]$ orbitals that are close to the Fermi level, should result in two rotational sequences with $\Delta i_x \approx 1\hbar$.

The alignments of the two negative-parity bands in ^{187}Tl in Figure 1, one of them being the known "$h_{9/2}$" band, are in the top panel, and they display a similar behaviour to the $h_{9/2}$ bands in ^{183}Au and ^{185}Au that are shown in the lower panels. Therefore, the new structure feeding the known "$h_{9/2}$" band is deduced to be the unfavoured signature.

3.2 Deformation of the prolate $h_{11/2}$ structure

Ref. [12] discusses how differences in the slopes and magnitude of alignments can be used to investigate relative deformations. For example, ^{188}Pb appears to have a slightly lower deformation compared to ^{180,182,184}Hg based upon its lower alignment (see Figure 2 in Ref. [12] and Figure 7 here). Similarly, the alignment of ^{186}Hg is less than ^{184}Hg at low spin. Also plotted is the alignment of the $11/2^-[505]$ band in ^{187}Tl, which seems to have a similar deformation to the prolate ^{186}Hg core (bottom panel), despite the previous calculation that predicted the $11/2^-[505]$ state in ^{187}Tl should have a lower deformation [3].

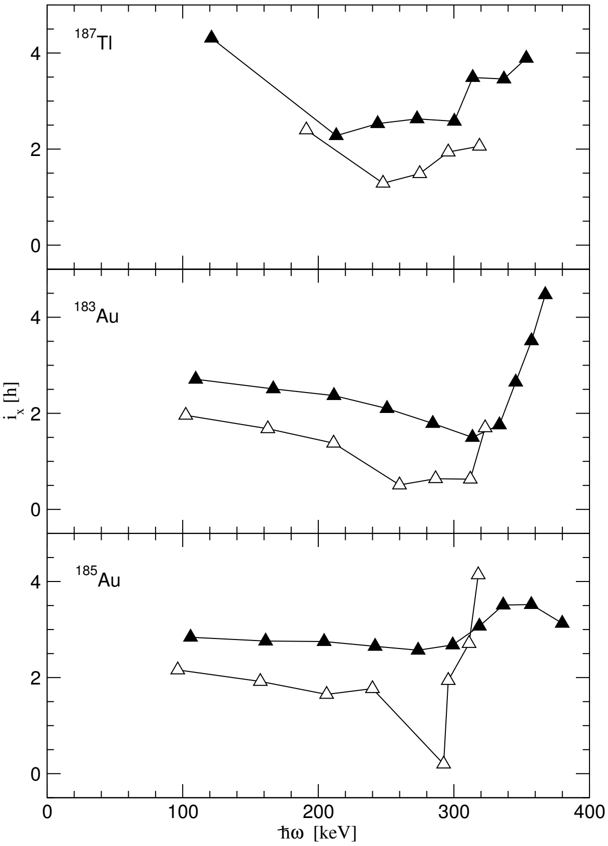

Fig. 6. Comparison of alignments for the prolate $h_{9/2}$ bands in ^{187}Tl, ^{183}Au [9, 10], and ^{185}Au [11]. Solid triangles correspond to the favoured signature, while open triangles are used for the unfavoured signature. The moment-of-inertia parameters are $\mathcal{I}_0 = 27\ MeV^{-1}\hbar^2$ and $\mathcal{I}_1 = 190\ MeV^{-3}\hbar^4$.

Upon closer examination, signature splitting can be seen in the $11/2^-[505]$ band at low spin, with the magnitude of the splitting decreasing at higher spin. Ref. [16] describes triaxial $11/2^-[505]$ bands in $N = 88 - 90$ nuclei that display such behaviour with $\gamma \sim -20^0$ (Lund convention [17]). The loss of signature splitting at high spin can be explained as a change towards axial prolate shape caused by the alignment of a pair of $i_{13/2}$ neutrons. We have performed potential energy surface calculations for this work (see Ref. [18] for the methodology) that predict a similar value of $\gamma \approx -18^0$ for the $11/2^-[505]$ state in ^{187}Tl.

An example of a calculation assuming a coupling between the $11/2^-[505]$ proton and a triaxial even-even core can be found in early studies on odd-mass Ir nuclei [19–21]. Their calculations approximately reproduce the experimentally observed states, providing strong evidence for the triaxiality of the $11/2^-[505]$ state in ^{185,187,189,191}Ir. Calculations for the present case of ^{187}Tl are in progress.

The presence of signature splitting in the oblate $9/2^-[505]$ and $13/2^+[606]$ states has been interpreted in Ref. [3] as possibly being due to triaxiality, although the present potential energy surface calculations predict both of these states arise from oblate, axially symmetric shapes with $\gamma = -60^0$.

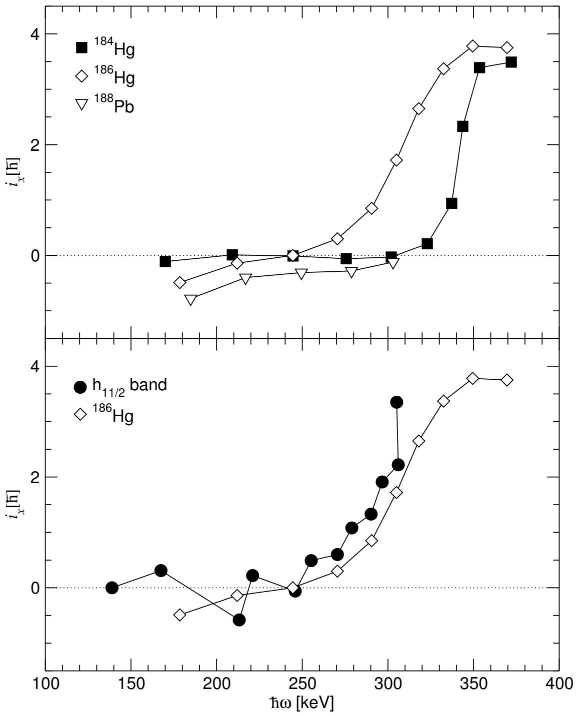

Fig. 7. Top panel: Alignment for the lowest prolate bands in the isotones of ^{187}Tl, ^{186}Hg [13] and ^{188}Pb [14], compared with their counterpart in the lighter even-even neighbour ^{184}Hg [15]. Bottom panel: Alignment for the lowest prolate band in ^{186}Hg compared with the alignment of the prolate $\frac{11}{2}^-$[505] band in ^{187}Tl. The moment-of-inertia parameters are the same as those used in Ref. [12], $\mathcal{I}_0 = 27\ MeV^{-1}\hbar^2$ and $\mathcal{I}_1 = 190\ MeV^{-3}\hbar^4$.

4 Conclusion

This paper reports on selected results from a study of ^{187}Tl, in particular, new information obtained for rotational structures built upon the $h_{9/2}$ and $h_{11/2}$ proton states. Evidence for the unfavoured signature of the prolate $h_{9/2}$ band is presented, based on alignment comparisons with $h_{9/2}$ bands in ^{183}Au and ^{185}Au where both signatures are known. In addition, the presence of the $11/2^-$[505] band was confirmed, with the previously known states [3] being rearranged and the band greatly extended. The $11/2^-$[505] state appears to have a larger deformation than was predicted by earlier calculations, and new self-consistent calculations performed for this work predict that the $11/2^-$[505] state has $\gamma = -18^0$, consistent with the observation of signature splitting at low spin.

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